FIBRE OPTIC VIDEO SIGNAL TRANSMISSION

A. Ramakrishna

Abstract

This report is a study on various aspects of multi-channel video signal transmission using optical fibers. Performance requirements for GMRT Intermediate Frequency (IF) links are similar in nature. Various modulation/demodulation formats for analog video signal transmission are considered. Transmission impairments are also studied. Developments in CATV (Cable Television) and satellite earth stations are reported. CATV has stimulated most of the research and development efforts on fiber optic analog video signal transmission.

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INTRODUCTION

Video transmission using optical techniques is attractive due to excellent characteristics of optical fibers like wide bandwidth, low transmission loses, light weight cables, and immunity to electromagnetic interference.

Fibre optic transmission is applicable for video transmission in Intermediate Frequency (IF) links, LO reference distribution, Cable Television (CATV) trunks, CATV distribution systems and broadband subscriber loops (viz. B-ISDN).

Fiber optic video transmission in analog format is advantageous because of cost effectiveness. Digital terminal equipment is very expensive due to the high cost of good video CODECs. Bandwidth utilisation of digital video transmission is poor. Digital video transmission will become feasiable only after consolidation of image compression standards and avaliability of inexpensive video CODECs.

Various modulation/demodulation formats for analog video signal transmission through optical fibers have been studied. These include:

1. Direct Intensity Modulation (DIM)

2. Amplitude Modulation (AM) of RF subcarriers

3. Frequency Modulation (FM) of RF subcarriers

4. Phase Modulation (PM) of RF subcarriers.

5. Pulse Modulation schemes such as:

   a. Pulse Amplitude Modulation (PAM)
   b. Pulse Frequency Modulation (PFM)
   c. Pulse Width Modulation (PWM)
   d. Pulse Position Modulation (PPM)

While evaluating the suitability of modulation schemes, we have to consider the special characteristics of fiber optic components (sources, detectors, cables) and their impairments.

During the course of investigation it will be shown that frequency modulation of an RF subcarrier (referred to as FM-SCM) is currently the most practical alternative for multichannel video signal transmission. Fiber optic transmission impairments like noise and nonlinearity will be studied. Emphasis is on implemented schemes and reported results from current published work.

APPLICATION AREAS:

CATV appears to be the single largest application area for video transmission. Most of the analog video R & D is targeted for CATV applications. About 87% of US homes subscribe to CATV. CATV is making inroads in Indian metropolitan areas also. Currently, CATV networks mostly use coaxial cable.

Fiber optic video transmission systems are of particular relevance to satellite earth stations. Satellite earth stations are generally located away from urban areas, to take advantage of low interference levels and weather conditions. Fiber optic links can be used to carry signals to and from the remote earth stations. There are some reported installations.

Wide bandwidth and excellent temperature stability (when buried below the surface) make fiber optic links attractive for phased array applications. Reported installations exist in large radar systems, satellite tracking stations and radio telescopes. Fiber optic links are the natural choice in RFI/EMI critical applications.

3. Nonlinear:

Fiber optic sources are not very linear. Current optical sources for analog application are an order of magnitude inferior to the best RF devices available.

It is interesting to note that satellite transmission systems are also power limited and nonlinear. Satellite terminal equipment is expensive. Currently, terminal equipment for high performance fiber optic links is also expensive. Consequently, both satellite and fiber optic channels are shared amongst many users. Analog schemes use FDM techniques for sharing the fiber optic link. This is referred to as Subcarrier Modulation(SCM). One of the reasons for FDM's popularity is the availability of good inexpensive microwave devices for FDM.

TRANSMISSION IMPAIRMENTS:

Analog transmission systems using semiconductor laser diodes (LD) enable larger repeaterless spans than do Light Emitting Diodes (LED) because of laser's high coupling efficiency with optical fibers. LDs also have higher modulation bandwidths than LEDs. However, in analog transmission systems using LDs, signal quality at the optical receiver deteriorates due to:

(1) Modal noise or speckle noise.
(2) Laser diode noise.
(3) Nonlinearity.

When multimode fibers are used modal noise is severe. LD noise and nonlinearity are further increased by reflected laser light.

NOISE SOURCES IN SCM SYSTEMS:

Four types of noise impair the detected signal in SCM systems. Shot noise is generated whenever current flows in a diode, with a power spectral density proportional to the detected photocurrent. Laser excess noise, normally described as Relative Intensity Noise (RIN) refers to noise generated in addition to shot noise, generated due the laser. Noise from the preamplifier

Some data communication links utilise CATV equipment and cables for cost effective implementation of WAN/LAN. These networks can be implemented on fiber without major modification.

PERFORMANCE REQUIREMENTS FOR VIDEO SIGNAL TRANSMISSION:

Video Signal Bandwidth	: 4.5 Mhz
No. of channels	: > 50
Signal-to-Noise Ratio SNR(weighed) at video baseband	: 56 dB
Composite Triple Beat (CTB)	: - 65 dB
Composite Second Order (CSO)	: - 65 dB
Cross talk	: -65 dB
Power Budget	: 10 dB

CTB and CSO are a measure of Intermodulation distortion and will be explained later on. (Current 550 Mhz. coax television systems are capable of delivering over 80 AM-VSB video channels with SNRs exceeding 47 dB).

IMPORTANT CHARACTERISTICS OF FIBER OPTIC TRANSMISSION

1. Large Transmission Bandwidth:
   Transmission bandwidth upto 10 Ghz. and beyond are not uncommon.

2. Power limited:
   Fiber optic links are power limited. Sources are available upto about 5 mw. Coupling power into fiber is difficult. Consequently, the power budget available is limited.

can be a significant impairment at high frequencies. Noise may also be generated by the system. This includes Modal noise and Laser Mode Partition Noise (LMPN) resulting from a combination of laser mode fluctuations and fiber dispersion. Thermal or front end noise and shot noise are well known and will not be discussed further.

Relative Intensity Noise (RIN):

RIN is defined as $RIN = \frac{\langle \Delta P^2 \rangle}{\langle P \rangle^2} / Hz$ where $\langle P \rangle$ is the average light intensity and $\langle \Delta P^2 \rangle$ is the mean-square intensity fluctuation spectral density of the light output. Laser diodes have intrinsic fluctuations in light output due to the statistical nature of the carrier recombination process. RIN decreases as the injection current increases.

$$RIN \propto \left(\frac{I_b}{I_{th}} - 1 \right)^{-3}$$

I_b - Bias Current
I_{th} - Threshold Current

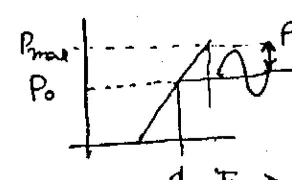
RIN includes not only intrinsic noise but also the reflection induced noise of the laser. RIN sets an upper limit on the fiber optic link performance.

$$CNR\ (RIN\ limited) = \frac{m^2/2}{RIN \cdot B}$$

B - Receiver Bandwidth

and m is the Optical Modulation Index (OMI) for one SCM channel. OMI is defined as

$$m_i = \frac{P_{max} - P_o}{P_o}$$



where P_{max} and P_o are respectively the maximum and average optical optical powers. Distributed Feedback (DFB) lasers have comparatively lower RIN. External cavity lasers have the smallest RIN.

Laser diodes are very sensitive to optical power reflected back into the cavity. Optical feedback gives rise to reflection peaks in the noise spectrum. These peaks are separated by
where n is the refractive index of fiber and L is the distance of the reflection surface from the laser. This degrades RIN of the laser. Carrier-to-noise (CNR) degradation due to reflections can

be as much as 20 dB. DFB lasers are very sensitive to reflections. DFB lasers used without optical isolators perform no better than Fabry-Perot (FP) lasers. When a Laser Diode is coupled to a multimode fiber, reflected speckle pattern can induce intensity fluctuations of a few dB.

Modal Noise

Modal Noise depends on the system configuration, the optical components and the laser mode characteristics. Laser spectrum may change due to reflections from connectors, external stress and change in temperature. Studies of modal noise levels have shown that it is impossible to achieve high quality video transmission with long lengths of multimode fiber. Modal noise is about - 155 dB/Hz for a 4 km. length of MM fiber. Superimposed pulse modulation can be used to bring this down to about - 125 dB/Hz. Superimposed pulse modulation spreads the laser spectrum.

Modal noise is absent when single mode fiber is used. However, when multimode lasers are used with SM fibers, laser mode hopping can lead to intensity fluctuations in the optical power coupled to the fiber. This appears as a kink in the current versus optical output curve of the laser diode. Thermal effects can lead to mode hopping.

Source Linearity and Inter Modulation Distortion

Light output from a laser is not a perfect linear function of the input current. This is due to the imperfections in device processing and dynamic effects. When a number of signals of different frequencies pass through a non linear device, energy is transferred to frequencies that are sums and differences of the original frequencies. The resulting distortion is called Intermodulation distortion (IMD). IMD can limit fiber optic system performance.

Linearity is usually characterised by the second and third order intermodulation products. These fall within the transmission bandwidth and are the dominant products.

Second order products are of the type $A \pm B$ ` $A, B = f_1, f_2 \cdots f_m$

Third order products are of the type $A \pm B \pm C$ $A, B, C = f_1, f_2, f_3 \cdots f_m$
f - carriers

In video systems, the terms CSO (Composite Second Order) and CTB (Composite Triple Beat) are used as measures for second and third order IMD products respectively.

CSO is the ratio, of the sum of second order IMD products to the carrier. CTB is the ratio, of the sum of third order products to the carrier.

It has been found that for large number of channels (n > 10)

CSO $\propto$ m^2(OMI per channel)
CTB $\propto$ m^4
m - OMI

CSO is temperature depend nt. CTB is frequency dependant.

The optimum operating condition for any SCM system constrained by nonlinearity, is a balance between, distortion and noise. Increasing m provides greater signal power but increases the distortion products generated. Second order products can be avoided by making the transmission bandwidth less than an octave (ie. $f_{max} < 2f_{min}$)

MODULATION ALTERNATIVES:

Modulation is the process of transforming the baseband video signal suitably, to match the transmission characteristics of the fiber optic link. Modulation schemes should exploit the characterstics of fiber optic links and should exhibit good immunity to fiber impairments. Some modulation schemes are discussed here

Direct Intensity Modulation (DIM)

In this scheme, the optical source (LD or LED) is biased to the mid point of its linear region. Baseband video signal is superimposed on the bias. Optical output of the laser can be written as:

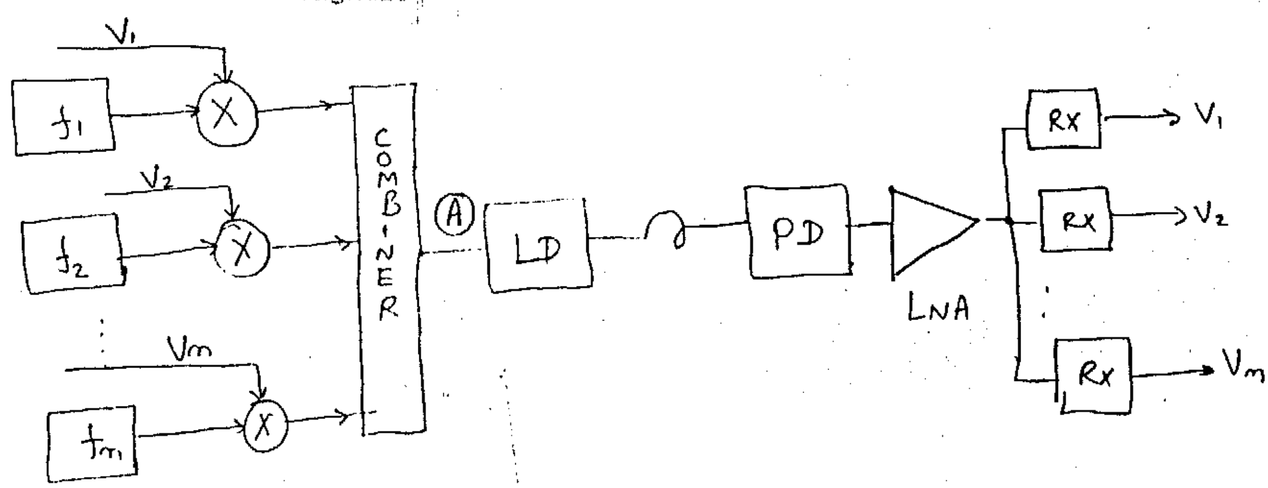
$$P_t = P_A [1 + M(t)]$$

P_t is the instantaneous light output, P_A the average light output and M(t) is the video signal. Only a single video channel can be transmitted. Therefore, DIM is restricted to video links using LED sources and low cost fiber.

Subcarrier Amplitude Modulation (AM - SCM)

This is a FDM technique wherein, each video channel Amplitude Modulates (AM) a separate RF subcarrier. This scheme is also referred to as AM-AM or AM-IM.

VHF/UHF Television and CATV utilise AM-VSB (Vestigal Side Band) for video transmission. Conversion costs will be minimal if AM-VSB can be utilised on the fiber optic link. AM-VSB is bandwidth efficient and requires marginally larger bandwidth than the base band video signal.



AM-SCM System.

V_1, V_2, ... Amplitude modulate sources f_1, f_2, ... respectively. The outputs are combined in a power combiner and the resultant output intensity modulates the source. Existing CATV networks can directly provide the combined signal at A . AM-VSB is the simplest and most convenient scheme for video transmission. However, it is extremely difficult to meet the performance requirements (SNR > 56 db, CSO, CTB < 65 db) using AM-SCM.

As seen earlier, RIN sets an upper limit for link performance using LDs. For a 40 channel AM-SCM system with OMI= 4% RIN should be < - 150 dB/Hz. for an SNR of 56 dB. This necessiates use of state of the art DFB lasers with optical isolators, low loss connectors and splices. For small OMI link is shot noise limited. When OMI is large output is clipped as the laser is driven below the threshold. CSO, CTB are proportional to m^2 & m^4 respectively. OMI is limited by nonlinerity of laser diode. Therefore, for AM-SCM systems low RIN, high power lasers are required.

AM-SCM is very inefficient in terms of optical power utilisation. Assuming shot noise limited performance, optical power of - 17 dBm/per channel is required at the receiver for an SNR of 55 dB. For identical performance, analog FM requires only - 52 dB/channel. (FM occupies more bandwidth).

Fiber Optic links are power limited therefore, at present AM transmission is not attractive for multichannel video transmission .

Experimental Multichannel AM video transmission schemes use high power lasers with external linearised modulators. Optical amplifiers can also be used to deliver the required optical powers. At present it is more economical to convert AM-VSB to FM than to use high performance lasers and optical devices.

Subcarrier Frequency Modulation (FM-SCM)

FM is widely used for Satellite Video Distribution and CATV microwave trunks. FM is a nonlinear modulation process. Ideally the modulated signal occupies infinite bandwidth. However, most of the power is contained within a reasonably small bandwidth. With FM it is possible to trade-off bandwidth for improved SNR. This is particularly suited to fiber optic links as they are power limited, with large transmission bandwidths. By using extra bandwidth, we can obtain SNRs better than CNR of the fiber optic link.

$SNR = CNR + F_{dB} + K_\omega$

F_{dB} is the FM advantage

K_ω is the emphasis gain (due to pre-emphasis, de emphasis)

$$F_{dB} = 10 \log \left[3(D_{pp}/f_v)^2 \cdot (b/2f_v) \right].$$

D_{pp} - peak-to-peak frequency deviation

f_v - Highest video frequency.

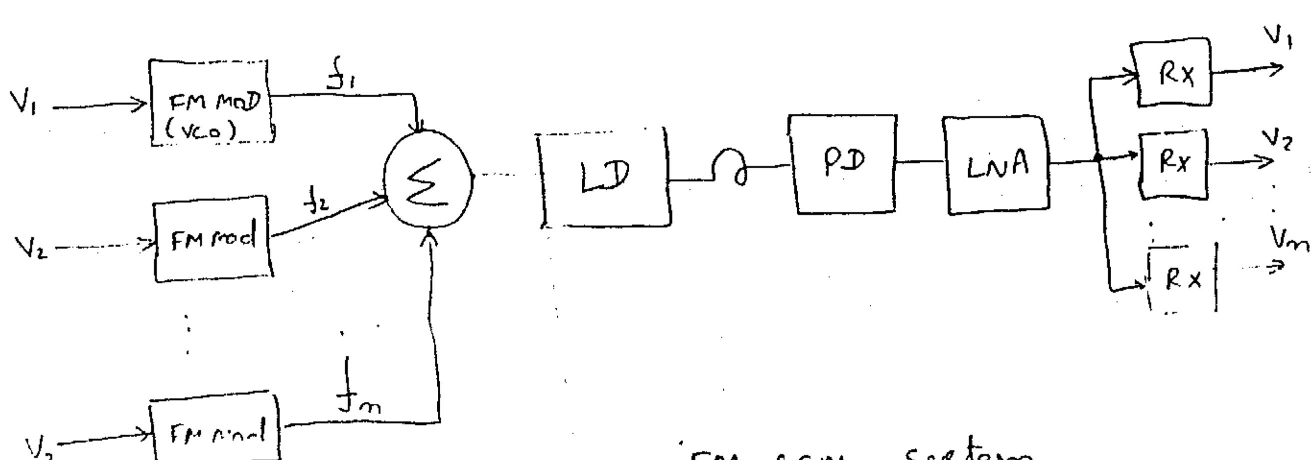
b - BW of Receiver.

Bandwidth occupied on fiber $\simeq D_{pp} + 2f_v \simeq 30$ MHz.

Typically, $F_{dB} + K_\omega \simeq 39.5$ dB

CNR required for an SNR of 56 dB is only 16.5 dB. The penalty paid is the increased bandwidth of $\simeq$ 30 Mhz.

For a CNR of 16.5 dB, RIN should be better than - 115 dB/Hz. This is easily achieved with commercial FP lasers. FM produces a constant envelope signal. Limiters can be used to reduce amplitude noise. FM receivers have greater immunity to noise. In multichannel systems, nonlinear distortion effects behave like random noise. Since OMI per channel is small(3 - 4%) laser noise is dominant, over the noise due to IMD. System linearity is much less critical with FM. Compared to AM, an FM system can simultaneously deliver more video channels, better signal quality and larger power budgets.



FM - SCM system

Each video channel, individually frequency modulates an RF subcarrier. These subcarrier signals are combined in a microwave power combiner and added to the laser bias, resulting in Intensity Modulation. At the reciever, the received signal is split and fed to individual FM receivers. Standard microwave techniques are used and most of the equipment is inexpensive as it is used extensively in satellite systems. RF frequencies are selected to match the satellite channel asignments. C-band (3.7 - 4.2 Ghz) being commonly used . Second order IMD products are avoided as the transmission bandwidth is less than an octave. Considering major noise terms, the CNR per unit bandwidth can be written as

$$\frac{1}{CNR} = \frac{2(F-1)KT}{m^2 I_D^2 R_D} + \frac{2 \cdot R_IN\, N_T}{m^2} + \frac{2 P_{IM}}{R_D\, G(I_D \cdot m)^2}.$$

Where F - Noise Figure of the LNA following the photo detector.

R_D - Input resistance of the LNA " " " "

m - OMI per channel

I_D - detected photocurrent (dc)

RIN - Relative Intensity Noise (includes Reflection induced Noise)

P_{IM} - IMD Noise Caused by system non linearity

Optimum OMI is a trade-off between laser RIN contribution and IMD noise contribution. When OMI is small, laser RIN dominates. When OMI is large, IMD products dominate. It has been shown that over modulation ($\Sigma m_i > 1$) does not degrade the performance much. This is because the video channels are not correlated and their peaks do not occur simultaneously. This permits biasing the laser beyond the mid point of the linear region. Neglecting laser RIN and IMD products, CNR is given approximately as:

$$CNR \simeq \frac{(m I_{dc})^2 R}{2 F K T B}.$$

R - Responsivity.
B - BW.

Some reported results using FM-SCM are listed below:

CHANNELS	OMI (Peak)	OMI (RMS)	SNR (WEIGHED)
120	336 %	30.7 %	56 dB
90	315 %	33.2 %	56 dB
60	462 %	59.6 %	56 dB .

Subcarrier Phase Modulation (PM-SCM)

Phase modulation of the subcarrier also allows bandwidth SNR trade-off. PM advantage is about 4.77 dB less than the FM advantage. Therefore, PM is rarely used.

Pulse Modulation:

Pulse modulation schemes for Analog transmission can only be used for small bandwidths (< 100 Mhz). Beyond 100 Mhz. it is difficult to make conversion equipment. From the standpoint of SNR performance, square wave FM (SWFM) and Pulse Frequency Modulation (PFM) are best.

SWFM is a variation of FM where the carrier is a square wave. SWFM offers the best receiver sensitivity when the fiber 6 dB bandwidth is less than 100 Mhz. SWFM also has the advantage of simpler, but non standard hardware. SWFM is attractive with LED transmitters. LED systems are cost effective, free from modal noise and fairly linear. With LED, optical power that can be coupled into a fiber is limited. SWFM with good receiver sensitivity suits LED systems. SWFM offers other advantages like:

(1) large dynamic range (30 dB without AGC)
(2) Small SNR fluctuations due to changes in fiber.

Digital Video Transmission:

It is not economical to digitise video signals for local and subscriber applications. Digital video transmission is employed for long distance transmission with regenerators. With analog transmission, SNR degrades with each regenerator. Presently, 45 Mb/s is adequate for good quality video transmission. Some very efficient digital modulation schemes have been reported and bandwidth utilisation will not be a problem. One scheme using SCM has reported an RF bandwidth efficiency of 1 bit/s per Hz, with a receiver sensitivity of -19.5 dBm over 48kms.

Digital transmission will dominate once inexpensive video CODECs become available. Standardisation of image compression algorithms will give a big boost to digital transmission. Local and subscriber applications are likely to make use of microwave subcarriers with digital modulation formats like MSK and FSK rather than using TDM. SCM allows mixed analog (FM) and Digital (FSK/MSK) transmission. Even now, CATV network utilise some digital channels for network management.

CHOICE OF COMPONENTS

LEDs are suitable when a small number of video channels have to be transmitted over short distances. LEDs are reliable, linear and free from modal noise. Power budgets with LED systems are small due to the difficulty in coupling power to the fiber.

Laser diodes are used when LED systems cannot provide the necessary power budget or modulation bandwidth. Except for very short distance links, single mode fiber is used for all analog video modulation systems. FP lasers are commonly used with FM-SCM systems. DFB lasers are used when improved RIN performance is necessary. External cavity and high power CW lasers with external modulators are used for AM-VSB systems.

Analog systems should use lasers with small threshold currents and linear light output vs. current characteristics. Relaxation oscillation frequency should be higher than the largest modulating frequency. Optical feedback by reflection has to be minimised. Optical isolators are used for this purpose. Angled butt connectors, whose end faces are obliquely polished at an angle to the fiber axis, should be used to minimise RIN degradation due to reflected light. Most manufacturers of high performance analog systems recommend their use. Index matching gel will also reduce optical feedback. Index matching gel is particularly helpful with InGaAs devices. n of InGaAs $\simeq$ 4.5.

P-i-n diode receivers are the simplest to design and use. APDs outperform P-i-n detectors, when the thermal noise contribution of the amplifier following the detector is significant or when the noise levels are high. In such situations, APDs offer better receiver sensitivities, without significant excess noise contribution. APD receivers are complicated and need high voltage bias and bias stabilisation circuits. At 850 nm Si APDs perform well and require a bias voltage of $\simeq$300 V. Longer wavelength Ge and InGaP APDs have large dark currents and excess noise.

CONCLUSION

Transmission of modulated RF subcarriers over optical fiber is an attractive approach for transport and distribution of multichannel video information. Subcarrier multiplexed techniques employ mature and low cost electronics technology. FM - SCM is particularly suited for multichannel video transmission in analog format.

SCM technology can also be used as a building block in many emerging lightwave systems such as, those employing dense wavelength division multiplexing and coherent detection techniques. Digital video transmission is likely to dominate in the future. SCM techniques allow co-existence of digital and analog modulation schemes, permitting a gradual transition to all digital networks.

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